

Shaking table testing of liquefaction potential of cemented paste backfill: Effects of backfill temperature

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ABSTRACT

Cemented paste backfilling has been successfully applied for mine ground control and/or tailings management in the past few decades. In the field, cemented paste backfill (CPB; a mixture of tailings, water and binder) can be subjected to different curing temperatures and/or seismic loadings (e.g., earthquakes and rock bursts) which can affect its geotechnical stability. Fresh CPB may liquefy due to seismic loading. However, no study has assessed the liquefaction of CPB under seismic conditions by using the shaking table test, particularly when the CPB is subjected to different curing temperatures. Accordingly, the shaking table test is applied to assess the effect of temperature on the possibility of earthquake-induced liquefaction of CPB. Shaking table tests are performed on CPB cured for 2.5 hrs under different temperatures. The results show that higher temperatures reduce the liquefaction susceptibility of CPB. The temperature of CPB therefore needs to be considered in evaluating its liquefaction susceptibility.

RÉSUMÉ

Au cours des dernières décennies, le remblayage en pâte cimentée a été utilisé avec succès pour le contrôle de terrain et la gestion des résidus miniers. Sur le terrain, le remblai en pâte cimentée (RPC) peut être soumis à diverses températures et/ou charges sismiques qui peuvent affecter sa stabilité géotechnique. Les RPCs peuvent se liquéfier en raison des sollicitations sismiques. Cependant, aucune étude n'a évalué la liquéfaction du RPC soumis à diverses températures à l'aide d'une table vibrante. La technique d'essai de la table vibrante est utilisée pour évaluer l'effet de la température du RPC sur son potentiel de liquéfaction. Des essais sur table vibrante ont été effectués sur des RPCs durcis pendant 2,5 heures et soumis à diverses températures. Les résultats montrent qu'une température plus élevée réduit la susceptibilité à la liquéfaction. La température du RPC devrait être prise en compte dans l'évaluation de sa sensibilité à la liquéfaction.

1 INTRODUCTION

The mining industry greatly contributes to the Canadian economy. However, mining also produces large quantities of potentially harmful waste (tailings) that may have negative impacts on public health and the environment if improperly disposed. Moreover, mining activities may create large underground openings (stopes) which might be susceptible to several different kinds of geotechnical engineering problems, such as ground subsidence (Jamali 2012, Farkish and Fall 2013).

A novel tailings disposal method called cemented paste backfilling has been developed to minimize the risks associated with mining activities and traditional means of mining waste management. Cemented paste backfill (CPB) is prepared by mixing 70% - 85% tailings, fresh or mine processed water, and often 3% - 7% (by total solid weight) hydraulic binder (usually cement) (Belem and Benzaazoua 2004, Aldhafeeri and Fall 2016, Haiqiang et al. 2016). Using CPB as backfill material for mine stopes allows large amounts of mining waste to be reused, which can increase the stability of the stopes (Thompson et al. 2009).

However, during seismic events (such as earthquakes or rock bursts), fresh CPB placed into mine stopes could be susceptible to liquefaction-induced failure which may cause worker injury/fatality and lead to significant environmental damage with economic repercussions (Abdelaal 2011, Alainachi and Fall 2019).

Mining regions in Canada have been subjected to several seismic events in the past. For example, north-eastern Ontario recorded five earthquakes with a

magnitude of 3.5 or higher between 1985 and 2016. Also, a 5.9 magnitude earthquake occurred in Saguenay, Quebec in late 1988 (Saebimoghaddam 2010).

There is the general consensus that the value of seismic parameters (such as the peak horizontal ground acceleration and duration of shaking) significantly affects seismic-induced liquefaction (Carter 1988). For instance, soil may liquefy under peak ground acceleration as low as 0.05 g (James et al. 2003). Furthermore, the liquefaction resistance of fresh CPB placed in mine stopes is greatly affected by the duration of shaking (Saebimoghaddam 2010, Sassa and Yamazaki 2017).

Previous studies have found that there are several heat sources that might affect the temperature of the CPB mass in the field. These sources include the internal heat produced during cement hydration, and the external heat that is related to the depth, geological conditions and geographic location of the mine (Aldhafeeri et al. 2016).

The shaking table technique has been used in several previous studies (e.g. Bairro and Vaz 2000, James et al. 2003, Pépin et al. 2009, Özgen et al. 2011, Mohamed 2014), to study the seismic-induced liquefaction of natural soils or tailings (without cement). On the other hand, other studies (e.g. Aldhafeeri and Fall 2016, Cui and Fall 2016) have been carried out to study the effect of the initial and curing temperatures on the strength of CPB. Although there are only a few studies that have evaluated the behavior of CPB under dynamic loading by using triaxial test such as Saebimoghaddam (2010), there are no studies to date that have evaluated the effect of temperature on the seismic response of CPB by using a shaking table. Accordingly, this study aims to evaluate the effect of the

backfill temperature on the liquefaction response of CPB during seismic loading by using a shaking table.

2 MATERIALS AND PROCEDURES

2.1 Materials

Silica tailings (ST) which are commercially available synthetic tailings that are made of ground silica (manufactured by U.S. Silica Co.) are used in this study as the main component of the CPB mixture. The mineral composition of ST is essentially quartz, which is a predominant mineral in tailings found in Canadian hard rock mines. The use of ST reduces the uncertainties found with natural tailings. Natural tailings contain different types of reactive minerals. These minerals can oxidize which produces different chemical compositions. The high percentage of silica (99.8% silicon dioxide (SiO₂)) makes ST a chemically inert material, and allows ST to minimize/control the potential chemical interactions of the tailings with other ingredients (e.g., cement, water) in the CPB mixture (Aldhafeeri and Fall 2016, Haiqiang et al. 2016). The grain size distribution of ST is plotted in Fig.1.

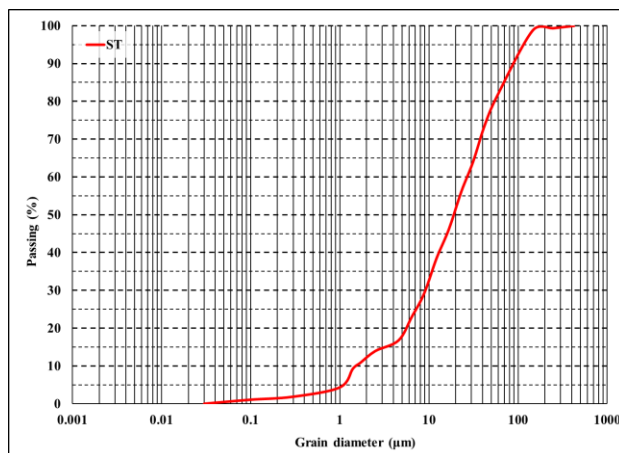


Figure 1. Grain size distribution of silica tailings.

2.2 CPB Preparation

The CPB samples were prepared by mixing ST with Portland cement type I (PCI; 4.5 wt%) and water for a water-to-cement ratio (w/c ratio) of 7.6. Prepared CPB mixtures have a bulk unit weight (γ) of 16.7 kN/m³, void ratio (e) of 0.9, and a yield stress of 170 Pa. In order to study the effect of the initial temperature on the seismic behavior of CPB, two different initial temperatures of 20°C and 35°C, were selected for study. After mixing was carried out, the CPB mixture was poured into a laminar shear box. To avoid evaporation of moisture, the laminar shear box with the CPB mixture was sealed and kept at a constant temperature or room temperature of 25°C for curing until a specific length of time elapsed; see testing program described as follows.

2.3 Setup and Instrumentation

In this study, dynamic loading is simulated by subjecting the samples to a series of 1-D (longitudinal) cyclic motions by using a computer controlled shaking table at the University of Ottawa (Fig. 2).

In order to examine the seismic response of CPB by using a shaking table, a flexible laminar shear box (FLSB) (Fig. 2) was designed and constructed at the University of Ottawa. The FLSB consists of 30 horizontal laminas made of aluminum alloy sections with dimensions of 31.7 mm x 31.7 mm. The inner dimensions of each lamina are 750 mm x 750 mm, and the clearance spacing between each lamina was designed to be 2 mm to ensure independent movement. The total capacity of the assembled FLSB is 750 mm x 750 mm x 1000 mm (W x L x H) (Alainachi and Fall 2019).

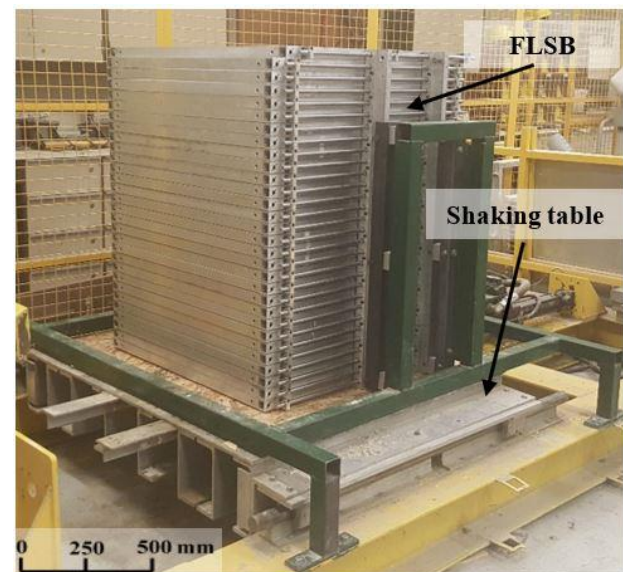


Figure 2. Shaking table and flexible laminar shear box

To contain/hold the CPB mixture, a flexible plastic bag was placed inside the FLSB. The high flexibility of this bag which only has a maximum thickness of 0.5 mm means that the bag has no or negligible effect on the movement of the FLSB. The prepared CPB mixture was poured into the FLSB. In order to avoid the overflow of CPB material during shaking and to accommodate the shaking table capacity of sample weight, the final dimensions of the CPB samples for testing are 750 mm x 750 mm x 700 mm.

Omega PX309 pressure transducers were placed at different levels in the CPB sample to monitor the changes in the pore water pressure (PWP) during shaking (Fig. 3). These transducers provide a pressure range from -15 to +15 PSI with an accuracy of $\pm 0.25\%$. The pressure transducers were connected to a signal conditioning and data acquisition system to record the data before, during, and after shaking. The data were recorded at intervals of approximately 1 s.

2.4 Experimental Test

The main goal of the testing is to evaluate the influence of the initial temperature on the seismic response of fresh CPB. In this regard, CPB samples were prepared under two different initial temperatures of 20°C and 35°C. Both samples were cured for 2.5 h.

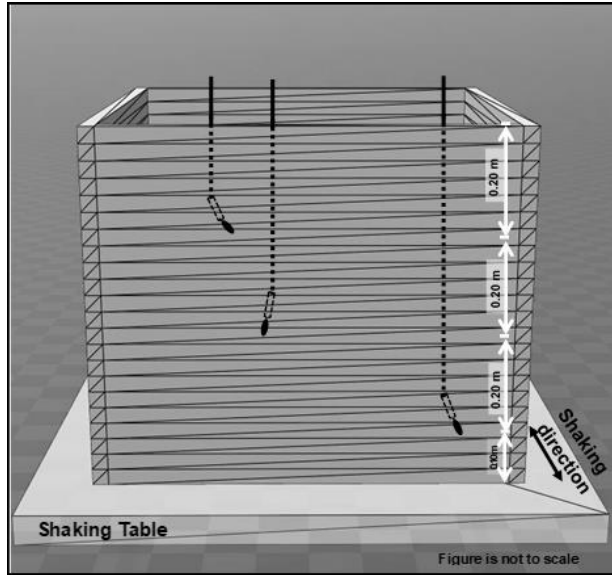


Figure 3. Schematic view of FLSB and location of instruments.

Before conducting the tests, and in order to simulate the ground shaking conditions, the seismic parameters of sinusoidal loading frequency (SLF), shaking peak horizontal acceleration (SPHA), horizontal displacement amplitude (HDA), and duration of the shaking (SD) were pre-determined as shown in Table 1.

Table 1. Summary of experimental test conditions

Test	Initial Temp. (°C)	HDA (mm)	SLF (Hz)	SPHA	SD (min)	CT (h)
1	20	32	1	0.13g	30	2.5
2	35	32	1	0.13g	30	2.5

HDA: Horizontal displacement amplitude; **SLF:** Sinusoidal loading frequency; **SPHA:** Shaking peak horizontal acceleration; **SD:** Duration of shaking; and **CT:** Curing time of CPB

The shaking tests are performed in this study at a sinusoidal loading frequency of 1 Hz in order to accommodate the sensitivity/limitations of the monitoring instruments. Although many earthquakes recorded in North America have a higher frequency (Nuttli 1973), nevertheless, it has been found that material subjected to seismic testing in the lab is insignificantly affected by the magnitude of the frequency of the applied seismic loading (Sriskandakumar 2004).

In order to accommodate the difference in scale between a real mine and a laboratory model, time scaling was applied to the ground motion. Thus, the duration of shaking in this study was set as 30 minutes (1800 s), even

though recorded earthquakes do not last for such a long period of time. This duration was used to allow good observation of the seismic behavior of the CPB and allow relative comparisons of the response, which is important for the future development of a constitutive model to describe the dynamic response of soils or tailings undergoing cementation under different initial temperature conditions. Likewise, previous studies on liquefaction (e.g. James et al. 2003, Pépin et al. 2012) have followed a similar procedure. Also, it was found that the cyclic peak of the liquefaction of tailings can be reached after around 1000 s of shaking (James et al. 2003).

It has been indicated in the literature that a peak ground acceleration of 0.05 g may cause soil/tailings liquefaction (Carter 1988, James et al. 2003). Therefore, the CPB samples in this study are subjected to a peak ground acceleration of 0.13 g, which is equal to the ground acceleration that was recorded in the Saguenay earthquake in 1988 in Québec.

Based on the above stated values of the loading frequency and peak ground acceleration, and by using the basic dynamic equation in (Douglas 2003, Chopra 2005), the deformation amplitude of ground motion in this study is determined to be 32 mm.

3 REPRESENTATIVE TEST RESULTS

The experimental results of shaking induced changes in the PWP and a liquefaction analysis with respect to the change in initial temperature are elaborated in this section. The parameters were evaluated at depths of 20 cm and 60 cm from the top of the sample cured for 2.5 h.

3.1 Changes in Pore-Water Pressure

Taking into consideration the expected changes in the PWP of the CPB material due to cement hydration, and to study the response of the CPB under seismic conditions, it is important to determine the initial conditions (hydrostatic conditions) of the CPB material prior to shaking by recording the PWP at each depth of the CPB sample before subjecting the sample to seismic loading.

The changes in the PWP of the two CPB samples at depths of 20 cm and 60 cm which are prepared at two different initial temperatures of 20°C and 35°C are plotted in Fig. 4.

Before shaking took place, there was a decrease in the PWP of both samples until the start of the shaking event. The decrease in PWP is related to water consumption due the progression of cement hydration (Scrivener et al. 2015). However, the CPB sample prepared at 35°C has a higher reduction in PWP because the high initial temperature accelerates cement hydration and causes additional consumption of the pore water (Aldhafeeri et al. 2016).

When the shaking began, there was a significant increase in the PWP (development of excess PWP) in the CPB prepared at an initial temperature of 20°C, while there was a small increase in excess PWP in the CPB prepared at 35°C; see Fig. 5. For instance, after 75 s of shaking, the maximum excess PWP developed at depths of 20 cm and

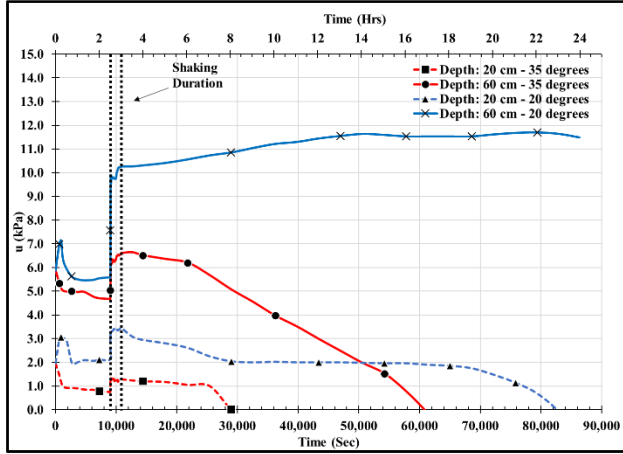


Figure 4. Changes in PWP at different depths of samples before, during and after shaking.

60 cm from the top of the CPB sample prepared at 20°C is around 1.1 kPa and 4.2 kPa, respectively. On the other hand, the maximum excess PWP developed at the same time and the same depths from the top of the CPB sample prepared at 35°C is 0.4 kPa and 1.5 kPa, respectively. The maximum excess PWP developed at depths of 20 cm and 60 cm from the top of the CPB sample prepared at 20°C after being subjected to shaking for 1600 s is 1.3 kPa and 4.6 kPa, respectively. The maximum excess PWP of the CPB sample prepared at 35°C is around 0.5 kPa and 1.8 kPa, respectively.

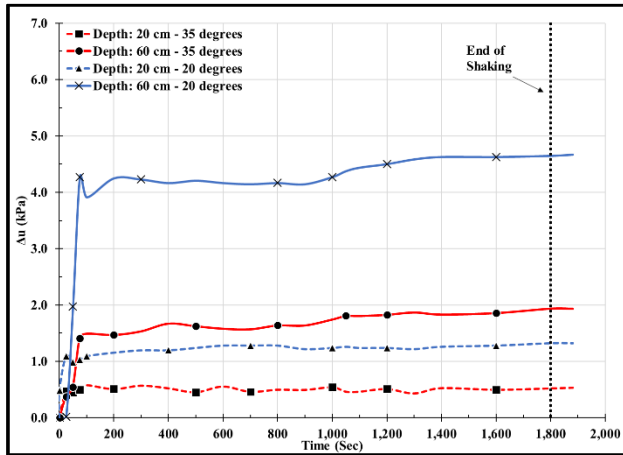


Figure 5. Excess PWP developed during shaking.

After the shaking ended, the PWP continued to increase in the CPB sample prepared at an initial temperature of 20°C. This can be explained by the contraction of the CPB particles due to the termination of the cyclic loading, which created additional PWP (Pépin et al. 2009). This is followed by relative stabilization of the PWP for each depth. Afterward, the PWP started to dissipate at a depth of 20 cm of the sample due to the combined effects of cement hydration and evaporation. On the other hand, there was no noticeable change in PWP (for around three hours) after shaking the CPB sample prepared at 35°C. Then, the PWP was rapidly reduced and

reached full dissipation at depths of 20 cm and 60 cm of the sample. This can be attributed to the acceleration of cement hydration due to the high initial temperature (Aldhafeeri and Fall 2016).

3.2 Liquefaction Analysis

There are several criteria for assessing liquefaction in the laboratory, such as those that are strength-, PWP-, and strain/deformation-based. As the change in PWP is considered to be the most essential component of the liquefaction process, the PWP-based criterion is the most basic and popular laboratory criterion because it depends on the change in PWP. The evaluation factor of the susceptibility of liquefaction in this criterion is the higher PWP ratio (R_u), which is the ratio of the change in PWP (Δu) and the initial effective stress (σ'_o). Liquefaction can be defined if $R_u \geq 1$, and if $R_u < 1$, there is no liquefaction (Jiaer et al. 2004).

Accordingly, R_u is determined for each tested CPB sample (Fig. 6) in this study by applying the following equation (Jiaer et al. 2004):

$$R_u = \Delta u / (\sigma'_o) \quad [1]$$

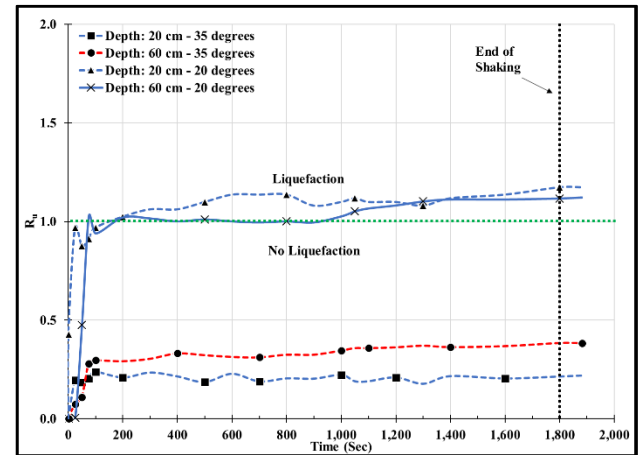


Figure 6. PWP ratio during shaking.

As shown in Fig. 6, the CPB sample prepared at 20°C is susceptible to liquefaction under the applied seismic loading conditions ($R_u \geq 1$), while the CPB sample prepared at 35°C resists liquefaction ($R_u < 1$). In other words, the higher initial temperature of CPB reduces its susceptibility to liquefaction under the studied seismic conditions.

4 DISCUSSION AND CONCLUSIONS

It is known that a higher initial temperature results in CPB material with a higher strength because the higher initial temperature increases the curing temperature and consequently accelerates the cement hydration process (Pokharel and Fall 2013, Cui and Fall 2016). Furthermore, the acceleration of the cement hydration process will lead to higher precipitation of the cement hydration products

(such as calcium silicate hydrate (C-S-H) and calcium hydroxide (CH)) which will increase the strength of the CPB material.

The difference in the behavior or liquefaction potential of the CPB samples prepared at 20°C vs 35°C can be attributed to the coupled effects of (i) the curing time and (ii) the temperature on the cement hydration, as discussed below.

(i) There is general consensus that the primary goal of using cement as the binder material in CPB mixtures is to bind the tailings particles, which increases the strength of the mixture (Jamali 2012). It is also commonly known that cement hydration progresses with time (Bullard et al. 2011). Cement hydration leads to a net reduction of the total volume of water and solids, which is known as self-desiccation. During the progression of cement hydration, there is precipitation of the cement hydration products, such as C-S-H and CH, in the CPB pores (Scrivener et al. 2015, Cui and Fall 2016). As a result, CPB particles will progressively bond together and the pore space between the particles will be reduced. This cement hydration will also cause a significant reduction in the water content in the CPB. Therefore, the PWP and moisture content of cementitious materials will decrease (Li and Fall 2016). Accordingly, liquefaction resistance gradually increases with the increase of these factors with time.

(ii) It is well documented that a higher initial temperature increases the rate of cement hydration. A high initial temperature increases the curing temperature which consequently leads to the production of more cement hydration products and intense self-desiccation (Nasir and Fall 2010, Aldhafeeri et al. 2016, Wang et al. 2016). This enhances the liquefaction resistance of CPB. Therefore, the CPB samples cured for 2.5 h do not liquefy during shaking when it is prepared at a temperature of 35°C.

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